Agricultural Applications of Austempered Iron and Steel Components

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ABSTRACT
Farmers, component designers, agricultural equipment manufacturers and after-market agricultural component suppliers have all found unique, cost-effective uses for austempered components. Austempered Ductile Iron (ADI), Austempered Gray Iron (AGI), Carbidic ADI (CADI), Austempered Steel and Carbo-Austempered™ Steel have all found applications in agricultural equipment and component applications. This paper will give the reader an overview of the processes, the salient properties of those processes, developments in the manufacture of said components, and specific case studies of their application.

INTRODUCTION
In 2002 Hayrynen and Brandenberg published the paper “Agricultural Applications of Austempered Ductile Iron”. The paper reviewed the properties exhibited by Austempered Ductile Iron (ADI) and its application in agricultural components. That paper has been widely distributed and has lead users to other austemper-based material/process applications in the agricultural equipment and component industry.

Many developments have occurred in the past few years that merit an updated review of austempering applications in the agricultural industry. This paper is an overview that includes ADI, Austempered Gray Iron (AGI), Carbidic ADI (CADI), Austempered Steel and Carbo-Austempered™ Steel. The authors will attempt to familiarize the readers with each of the processes and the engineering, manufacturing and economic advantages of the aforementioned material/process combinations.

BACKGROUND
Austempering is an isothermal heat treating process that can be applied to ferrous materials to increase their strength and wear resistance without sacrificing toughness. Austempering consists of heating a ferrous material above the critical temperature (red hot), soaking at that temperature for a time sufficient to result in a uniform temperature and microstructure, cooling rapidly enough to avoid the formation of pearlite to a temperature above where Martensite forms (Ms) and then holding (Austempering) for a time sufficient to produce the desired matrix structure. In steel, the resultant microstructure is a combination of acicular ferrite and fine, complex carbides. This multi-phased structure, named after its discoverer, Edgar Bain, is called “Bainite”. In cast irons, with excessive carbon in the form of graphite, and higher silicon contents, the resultant matrix consists of a mix of acicular ferrite and carbon stabilized austenite, collectively called “ausferrite”. Figures 1 and 2 provide schematic isothermal transformation diagrams for the austempering of steel and cast iron, respectively.

The strength level in austempered steels and irons will largely be determined by the austempering temperature. A higher austempering temperature will produce a material with a lower strength and hardness, but greater toughness and ductility. A lower austempering temperature will produce a higher strength and hardness material that has somewhat lower toughness and ductility. The “grade” or “hardness” of the material/process combination selected will be determined by the engineering, performance and economic factors defined by the end user and producer.

Because austempering is an isothermal process, it offers several advantages over conventional quenching and tempering and other methods of martensitic hardening. The martensitic transformation takes place when the local material temperature drops below the Martensite Start (Ms) temperature. Therefore, the transformation (by definition) takes place at different times in sections of differing section modulus. This can result in inconsistent dimensional response, micro-, and even macro-cracking.
A schematic isothermal transformation diagram for a medium carbon steel with the austempering (green) and quench and tempering (red) processes is shown.

Figure 1

A schematic isothermal transformation diagram for a typical (3.5%C, 2.5%Si, 0.3%Mn) cast iron with the austempering process is shown.

Figure 2

Since the formation of bainite and ausferrite occur uniformly throughout the part, over many minutes or hours, austempered components exhibit very consistent dimensional response and no cracking (either micro or macro).

ADI, AGI and CADI are generally lower cost replacements for steel and aluminum castings, forgings and weldments. Austempered steel and Carbo-Austempered™ steel are generally chosen when engineering and performance requirements exceed those available from conventional material/heat treating combinations.

AUSTEMPERED DUCTILE IRON (ADI)

ADI is produced by austempering a ductile iron (spheroidal graphite iron) material to produce an ausferritic matrix. The spheroidal graphite nodules in ductile iron allow us to fully exploit the high strength and toughness of ausferrite as they do not reduce the toughness of the iron as do graphite flakes or large carbides. Table 1 shows the properties of the ADI grades specified in ASTM A897/A897M-06 (2011). Furthermore, ADI is about 10% less dense than steel due to the presence of these graphite nodules.

Engineers and designers have learned that ductile iron can be easily cast into complex shapes. By subsequently austempering these castings, they can exhibit a strength-to-weight ratio comparable to heat treated steel or aluminum. This allows designers to create one-piece designs that were previously assembled from multiple forgings, castings, extrusions, weldments or stampings.

ADI’s microstructure (ausferrite) contains carbon stabilized austenite which is thermally stable but, when acted upon by a high, normal force, transforms locally to untempered martensite nested in a ferritic matrix. This dramatically increases the surface microhardness giving ADI an abrasive wear resistance that exceeds that implied by its bulk hardness.

In certain angular and rocky soils, ADI plow points, boots and plow shins have been reported by farmers to outwear hard-face welded and high-chrome, wear resistant irons. In other, less aggressive soils, ADI does not perform as well. In these applications, CADI is generally chosen and will be discussed later in this paper.

The same “strain transformation” phenomenon that increases surface hardness also induces compressive surface stress which, in turn, increases allowable bending stress. The result is an increase in the fatigue strength of both structural and powertrain components which can benefit greatly from shot peening, grinding or fillet rolling after austempering.

There is much more technical information available on ADI’s fatigue behavior, machinability and other important design and manufacturing characteristics but the scope of the entire body of information exceeds the scope of this paper. Additional sources can be found within the reference and additional reading sections.
Ground engaging applications are considered by many to be some of the most difficult to engineer due to the abrasiveness of environments on the equipment. The Rangeland Planter Boot shown in Figure 3 is one where exceptional wear resistance, coupled with a detailed casting design, was required for a very specific and tough application; the replanting of arid, wilderness grasslands. The incumbent steel weldment (Figure 3a) used for the application was not holding up to the environmental and functional design needs of a seed planter. The ADI solution to the weldment’s issues is shown in Figure 3b.

The steel fabrication did not hold up to the rigors of the harsh, wilderness terrain in either wear resistance, or strict seed flow-through parameters. The steel weldment wore through after only 500 acres of planting; necessitating an expensive and time consuming field replacement. The welded design also lacked the smooth, internal transitions needed for precise seed flow.

The redesigned ADI casting (shown installed on the planter in Figure 4) meets the difficult requirements while posting a 15% reduction in part weight, cutting the manufacturing lead time in half (from six weeks to three weeks), better than doubling the life of the boot, and reducing the part cost by more than 65%. This conversion was the recipient of the 2007 Engineered Casting Solutions / American Foundry Society Casting of the Year Award.

Sometimes ADI is simply chosen for its low cost to manufacture. That is the case with the small ADI lever arm shown in Figure 5. This arm is an alternative to forged steel. It is cast in ferritic/pearlitic ductile iron, machined completely and then austempered giving the end user the low product cost and durability that they need.

<table>
<thead>
<tr>
<th>Tensile Strength (MPa / ksi)</th>
<th>Yield Strength (MPa / ksi)</th>
<th>Elongation (%)</th>
<th>Typical Hardness (HBW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>750 / 110</td>
<td>500 / 70</td>
<td>11</td>
<td>241 - 302</td>
</tr>
<tr>
<td>900 / 130</td>
<td>650 / 90</td>
<td>9</td>
<td>269 - 341</td>
</tr>
<tr>
<td>1050 / 150</td>
<td>750 / 110</td>
<td>7</td>
<td>302 - 375</td>
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<tr>
<td>1200 / 175</td>
<td>850 / 125</td>
<td>4</td>
<td>341 - 444</td>
</tr>
<tr>
<td>1400 / 200</td>
<td>1100 / 155</td>
<td>2</td>
<td>388 - 477</td>
</tr>
<tr>
<td>1600 / 230</td>
<td>1300 / 185</td>
<td>1</td>
<td>402 - 512</td>
</tr>
</tbody>
</table>

Table 1. A summary of the minimum properties of the six grades of ADI specified in ASTM A897/A897M-06(2011).
Figure 5. A small ADI actuating lever for a European agricultural application is shown.

Many types of wheeled agricultural and construction equipment are being converted to rubber tracks for increased versatility, lower weight, cost and soil compaction. In one application, the main drive wheel consisted of an 84-piece welded and bolted steel assembly. A one-piece ADI design that proved to be lower in cost and more durable is shown in Figure 6. Because 84 pieces of steel were replaced with one, green sand, ADI casting, the wheel reliability was improved by eliminating the inherent variabilities in cutting, stamping, drilling, bolting and welding the components together.

Figure 6. A Toro Dingo TX drive system is shown in (a) along with the entire vehicle in (b). The one-piece ADI main drive wheel that replaced an 84-piece steel welded and assembled component is shown in (c). (Courtesy of Toro and Smith Foundry.)

The earliest agricultural applications of ADI were simple aftermarket plow points and wear shins. Figure 7 shows a typical ADI plow point that has been in production for more than 20 years. These through-hardened ADI ground engaging parts replace hardened and hard-faced welded steel components at a competitive price.

Figure 7. A typical ADI plow point is shown.

Australian farmers have utilized the prize-winning MitchTip design since the 1990's (Figure 8). This proprietary ADI design utilizes impacted soil to extend the life of the tip. An "engineered CADI" version with a brazed on carbide tip and a durable ADI body is also available. MitchTips have proven equal to the task of ripping abrasive Australian soils.

Figure 8. A photograph of ADI MitchTips from Australia is shown.
Figure 9 shows a patented and simple to use Agri-Speed Hitch that consists of two main components with five ductile iron sub-components, of which, four are ADI. It allows the operator of a tractor to safely back up and hook, or unhook a wagon without leaving the tractor. Ductile iron, and ADI replaced steel in this application to reduce the cost and improve the durability of the hitch. This device was awarded a “Best in Class” in the 2008 Engineered Casting Solutions / American Foundry Society casting competition.

Figure 9. This Agri-Speed hitch uses four ADI components.

Agricultural components must often withstand impact loading and the abrasive wear characteristics of sandy and/or wet grass, stalks and organic material. The ADI flail shown in Figure 10 is an elegant, cost effective design that puts the rotating mass where it is needed.

Figure 10. An ADI rotating flail for an agricultural mower-conditioner is shown. (Courtesy of Buck Foundry)

AUSTEMPERED GRAY IRON (AGI)
AGI provides the same excellent wear resistance as it’s ausferritic cousin, ADI. AGI exhibits much higher strength than as-cast gray iron. Figure 11 shows the tensile strength array of Class 20, 30, and 40 gray iron as-cast and austempered at 371°C (700°F), 316°C (600°F) and 260°C (500°F). Its most salient feature is its ability to damp noise due to the combination of an ausferritic matrix and large graphite flakes. Note that Figure 12 shows that as the austempering temperature is decreased, the strength of the AGI increases, as does the damping coefficient. Those graphite flakes also limit the strength of AGI, acting as angular voids in the metal matrix and allowing maximum strengths no higher than around 450 MPa.

Figure 11. The tensile strength of gray iron Classes 20, 30 and 40 as-cast and austempered at 371°C (700°F), 316°C (600°F) and 260°C (500°F) are plotted.

Figure 12. The damping coefficient of three classes of gray iron as-cast gray iron and austempered at three different austempering temperatures are plotted.

The advantages of AGI are its low cost and excellent castability. This makes it a good candidate material/process combination for applications that require low cost, a complex shape, good strength and wear resistance where impact and cyclic stresses are not significant.
The most ubiquitous application of AGI is in cylinder liners for diesel engines. In this application, the cylinder liners offer good wear resistance and noise damping as well as improved burst strength over as-cast gray iron liners.

**CARBIDIC AUSTEMPERED DUCTILE IRON (CADI)**

CADI is produced by the introduction of carbides into the cast iron matrix during the casting process. The iron is subsequently austempered in a manner that produces a controlled percentage of carbides in an ausferritic matrix. CADI was introduced in 1991 to produce components with better wear resistance than ADI at a price (and performance) competitive with abrasion resistant irons, but with a modicum of impact strength. Figure 13 shows the abrasive wear resistance of CADI vs. an array of other engineering materials.

![Figure 13. Pin abrasion performance of 5% and 18% carbide CADI vs. other engineering materials is plotted as a function of hardness (HRC).](image)

CADI may also be produced by mechanically introducing carbides into a casting cavity prior to the introduction of molten metal. The subsequent austempering of the component does not affect the cast-in carbides. Another version of CADI can be produced by casting a part as ductile iron, hard-face welding a locality on the part and then subsequently austempering it, leaving the carbide hard-face weld unaltered, while producing a base matrix of ausferrite.

The first commercial application of CADI occurred in 1991. A small agricultural implement manufacturer then using ADI needed “a little more wear resistance” on a certain fully-supported plow point (Figure 14). A casting process to produce an as-cast iron matrix containing mixed spheroidal graphite and carbides was developed. The carbides were subsequently partially dissolved during austenitizing before being quenched to complete an austemper heat treatment. The resulting wear resistance was suitable for the customer’s application and the parts exhibited adequate toughness to survive initial dropping of the plow and impacts with stones.

![Figure 14. The first, commercial CADI application (circa 1991) was this small plow point. (Courtesy of Carroll Agricultural.)](image)

Harvesting machines pose interesting challenges to design engineers. If the handling and thrashing components are too soft, they will wear out, causing downtime at critical harvest times. If those same components are too brittle, they may break, causing the machine to be off-line at a critical time. Engineers have found that CADI rasps, thrashing tines, flights and buckets can withstand the impacts sustained in grain harvesting and provide sufficient wear for a full season and more.

**AUSTEMPERED STEEL**

Austempering of medium carbon and alloyed carbon steels provides superior strength, toughness and resistance to environmental embrittlement at hardness ranges exceeding 40 HRC. Figure 15 shows the relative insusceptibility to hydrogen embrittlement of bainite vs. tempered martensite in a bend test.

Austempering of medium and high carbon steels produces a fine, acicular matrix of ferrite peppered with very fine complex carbides called “bainite”. For hardenability in excess of 40 HRC, bainite exhibits significantly greater ductility than comparable martensitic structures. Table 2 compares the properties of austempered and quenched and tempered AISI 1090 steel torsion bars.

Austempered steels are adopted when low distortion, good toughness and environmental stability at tensile strengths in excess of 1400 MPa are required.
Figure 15. This figure shows that austempered 4340 steel is less susceptible to environmental hydrogen than quenched and tempered 4340.

Table 2. A property comparison of bainite compared to martensite in AISI 1090 torsion bars.

<table>
<thead>
<tr>
<th>Mechanical Property</th>
<th>Bainite</th>
<th>Martensite</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hardness (HBw)</td>
<td>415</td>
<td>388</td>
</tr>
<tr>
<td>Tensile Strength (MPa)</td>
<td>1415</td>
<td>1380</td>
</tr>
<tr>
<td>Yield Strength (MPa)</td>
<td>1020</td>
<td>895</td>
</tr>
<tr>
<td>Elongation (%)</td>
<td>11.5</td>
<td>6</td>
</tr>
<tr>
<td>Reduction in Area (%)</td>
<td>30</td>
<td>10.2</td>
</tr>
<tr>
<td>Fatigue Cycles</td>
<td>105,000</td>
<td>58,600</td>
</tr>
</tbody>
</table>

The tiller tines shown in Figure 16 are produced in hot rolled, medium carbon steel austempered to a hardness in excess of 40 HRC. Austempered steel is used in this application for its toughness and wear resistance.

Austempered steel has also shown itself to provide useful properties in powertrain applications like shafts, clutch plates and gears. Figure 17 shows an austempered steel output shaft. This material/process combination was chosen for this application for its low distortion and high torsional strength.

Figure 16. Austempered, medium-carbon steel is used for these production tilling tines.

Figure 17. Austempered steel output shafts for an Agricultural equipment application are shown.

CARBO-AUSTEMPERED™ STEEL

Carbo-Austempering™ is a process that puts a high-carbon, bainitic case on a lower carbon bainitic or martensitic core. Its most salient property is very high toughness and impact strength and high-load, low-cycle fatigue strength. Figure 18 compares the bending fatigue strength of Carbo-Austempered™ and carburized and hardened 8822 steel. Carbo-Austempered™ steels can have surface hardnsses approaching 60 HRC without the attendant loss of toughness evident in carburized and hardened structures.

Often, the application of Carbo-Austempering™ is tried when all else has failed. Figure 19 shows several examples of Carbo-Austempered Steel™ for pump shafts, split rings and output shafts. In each case, the designer sought to have low distortion with good wear resistance and fatigue strength.
Austempering offers manufacturers numerous opportunities to make their iron and steel components tougher, stronger, lighter, quieter and more wear resistant.

ADI is a cost effective, durable alternative to steel and aluminum castings, forgings, weldments and assemblies.

AGI combines good wear resistance and noise damping at a total manufacturing cost less than ADI, steel or aluminum.

CADI offers extreme wear resistance with a modicum of toughness that gives it performance and cost advantages over conventional abrasion resistant iron components.

Austempered steel components exhibit low, consistent growth during heat treatment, and superior strength and toughness at hardnesses exceeding 40HRc.

Carbo-Austempered™ steel components allow up to 50% higher bending loads (compared to carburized steel) in the high-load, low-cycle fatigue range.

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REFERENCES


ADDITIONAL READING

2. Ductile Iron Data for Design Engineers, revised 1998
3. AGMA 939 A07 Austempered Ductile Iron for Gears,
American Gear Manufacturers Association,
www.AGMA.org.
4. ISO 17804:2005, Founding Ausferritic Spheroidal
5. 1st International Conference on Austempered Ductile
Iron: Your means to Improved Performance, Productivity
6. 2nd International Conference on Austempered Ductile
Iron: Your Means to Improved Performance, Productivity
and Cost, Ann Arbor, MI, USA www.afsinc.org.
7. 1991 World Conference on Austempered Ductile Iron,
Chicago, IL, USA. Individual papers available from
8. Proceedings of the 2002 World Conference on ADI,
“Conference on Austempered Ductile Iron (ADI) for
Casting Producers, Suppliers and Design Engineers,
and Steels, “Heat Treating and Properties of Ductile

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